EXPERIMENTAL INVESTIGATION AND NUMERICAL MODELLING ON THE AXIAL LOADING OF JET GROUTING COLUMNS

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Abstract

The objective of the present paper is to analyse, by means of combined experimental investigations and numerical simulations the load settlement response of axially loaded jet grouting columns with the aim of defining a theoretical methodology for the design of jet grouting reinforced foundations. The results of a well documented experimental campaign including full scale axial loading and pull-out tests on different jet grouting columns are first presented together with preliminary investigations. Interpretation of the load settlement response is then performed by a back analysis with a finite element code. Adopted model allows interpretation of interaction between columns and surrounding soil and a back analysis of the load transfer mechanisms taking place along the shaft and the base of columns. This analysis has been conducted by focusing on the role of the characteristics of jet grouting columns.

Streszczenie

Przedmiotem artykułu jest przedstawienie wyników analiz numerycznych, wykonanych dla kolumn iniekcyjnych obciążonych osiowo. Wyniki analiz numerycznych przedstawiono w połączeniu z wynikami próbnych obciążeń kolumn, w celu zdefiniowania teoretycznej metodologii dla projektowania zbrojonych fundamentów z kolumn iniekcyjnych. W pierwszej kolejności przedstawiono wyniki dobrze udokumentowanych doświadczeń wciskania i wyciągania kolumn iniekcyjnych wraz z wstępnymi badaniami. Interpretację krzywej „obciążenie – osiadanie” przeprowadzono wykorzystując analizę wsteczną z zastosowaniem elementów skończonych. Zaadoptowany model pozwala na interpretację współpracy kolumn iniekcyjnych z otaczającym je gruntem oraz analizę wsteczną mechanizmu przekazywania obciążenia przez pobocznicę i podstawę kolumn. Analizę numeryczną przeprowadzono z uwzględnieniem rzeczywistych wartości parametrów materiałowych kolumn iniekcyjnych.

Keywords: **Jet grouting column; Field trial test; Numerical simulations.**

1. INTRODUCTION

Jet grouting columns are frequently adopted in foundation engineering as an alternative to piles with the aim of strengthening weak subsoil and transferring loads to deeper and more competent strata. In some cases treatments are spanned very close to each other, in order to form a unique massive body made of overlapped columns [8], particularly effective where the required performance consists in a strong reduction of settlements and in improving the resistance to horizontal loads. The second most frequently adopted solution consists of regularly spaced arrays of isolated columns, forming a support system similar in principle to a piled foundation. In both cases steel bars, casing or H piles can be inserted in fresh or hardened cemented soil (soilcrete) to provide columns with tensile and flexural strength or additional compressive resistance. Arrays of isolated columns have been adopted in a large number of cases both for foundation of new structures ([12], [21], [23]) or for underpinning of pre-existing ones ([13], [17], [24]).

In order to effectively dimension these foundation systems, geometry and stress-strain properties of the cemented soil portions must be known in advance together with the interaction between columns and surrounding soil. Concerning the former aspect empirical relations ([11], [16]) and theoretical formulations [19] have been produced to predict dimensions and mechanical properties of columns for assigned soil properties and injection system.

Concerning the interaction with the surrounding soil several authors ([4], [7], [17]) have presented full scale experiments where excellent performances are shown by jet grouting columns subjected to axial loading and pull-out tests. In particular Garassino [14] and Maertens and Maekelberg [17] back calculated unit resistances similar or larger than those given by standards on driven piles in similar subsoil conditions. The same conclusions were derived by Bustamante [4] who collected a large number of results from axial load tests performed on jet grouting columns instrumented with removable extensometers. His back analysis showed that axial loads are preferably transferred to the surrounding soil by the shaft friction with ultimate tangential stresses almost twice as those reported in literature on bored piles [22].

While those results are indicative for failure analyses, the knowledge of stress mobilisation at the column boundaries and particularly along the shaft, is a fundamental step for prediction of foundation settlements. On this issue Maertens and Maekelberg [17] generally noticed that displacements necessary to mobilise lateral stress on axially loaded jet grouting columns are larger than for displacement piles.

In spite of these experimental evidences, there is lack of analytical models able to predict the load settlement response of jet grouting columns under general conditions. The present work is aimed to analyse the mechanisms of load transfer from axially loaded columns to the surrounding soil. Quantification of load transfer functions at the shaft and lower base of axially loaded jet grouting columns is here obtained by back analysing the results of field trial tests with a finite element model.

2. FIELD TRIAL LOAD TESTS

Presented experimental campaign has been carried out in the municipality of Bojszowy – Poland ([5], [6]) on four trial jet grouting columns, each of them 7.0 m long, located at the corner of a 5.0 m side square array. Nine anchoring steel reinforced jet grouting columns, each of them 11.5 m long, have been created at the corner of a larger array to provide reaction to the applied loads (Fig. 1).

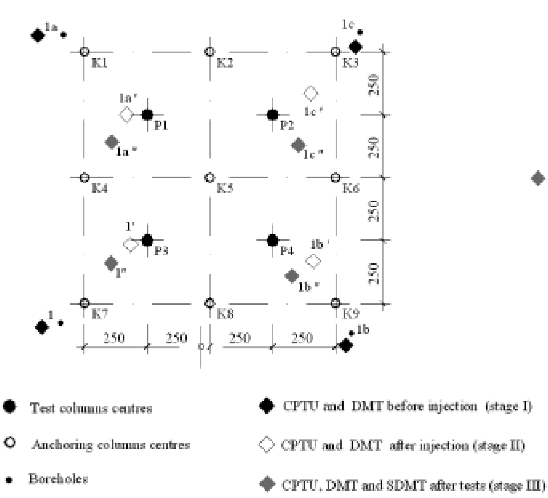

Figure 1.
Layout of the test site with location of CPTU, DMT and SDMT tests [6]

The subsoil has been investigated up to a depth of 15 m from the ground level by means of static CPTU penetration tests, dilatometer DMT and SDMT tests (Fig. 1). In an attempt to evaluate possible modifications induced on the subsoil by the injection of columns and by the axial loading, these tests have been repeated in the proximity of columns shafts before and after operations (I. before columns injection; II. after columns injection; III. after trial loading). The following conclusions can be drawn based on observation of a sample of in situ test results (Fig. 2):

- according to both CPTU and DMT indexes, the soil can be classified as a sand with water table located at a depth of about 2.5 m from the ground level;
- compared with the lower profile, higher tip resistance q_c and higher KD and ED indexes are obtained in the top 3 m, probably as an effect of

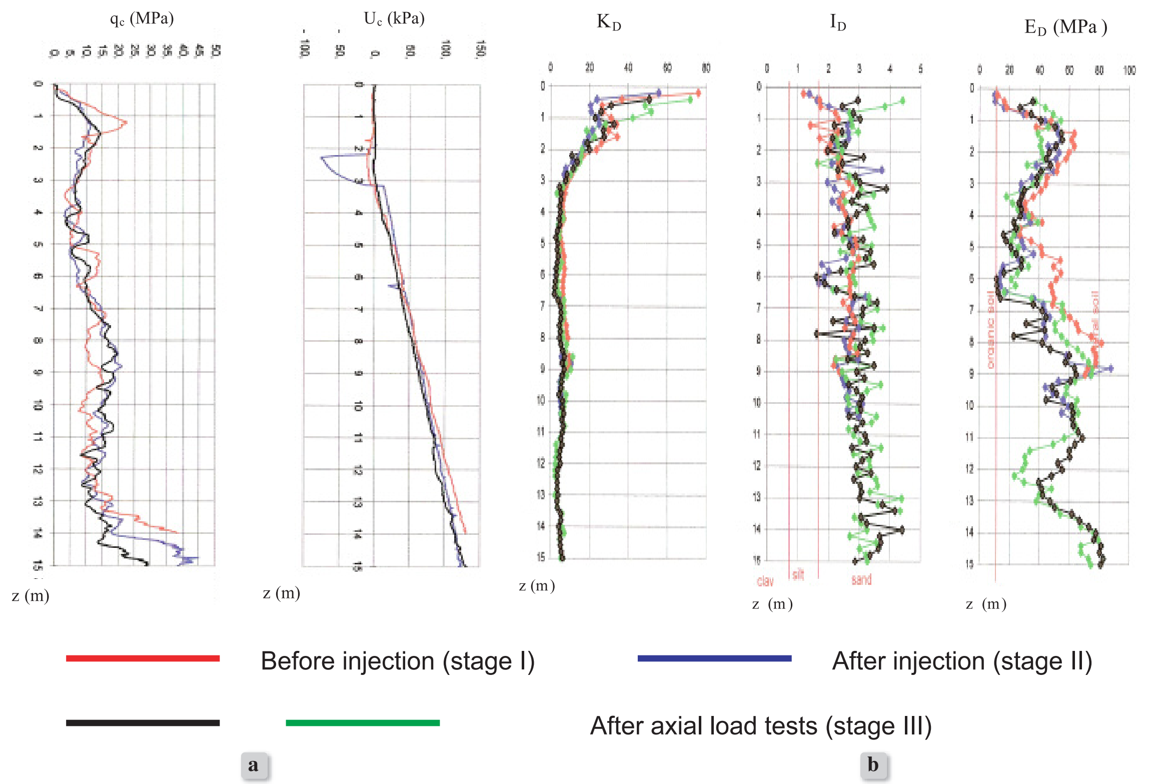

Figure 2.
Sample of in situ test results a) CPTU test; b) DMT test [6]

past water table oscillations;

- profiles retrieved at different stages are quite repeatable without remarkable effects of columns injection and trial loading.

The trial columns (identified as P in Fig. 1) were created by adopting the set of injection parameters listed in Table 1. In order to provide additional compressive strength or tensile resistance necessary for the uplift tests, three of these columns (P1, P2 and P4) were equipped with a HEB 240 reinforcing steel bar inserted soon after injection.

The mechanical properties of soilcrete were investigated by performing a large number of uniaxial compression tests on samples cored from the trial columns and equipped with lateral strain gauges. The tests gave the following average values of uniaxial compressive resistance, Young's modulus and Poisson ratio:

$$\sigma_c = 21.12 \text{ MPa}; \quad E_{50} = 9888 \text{ MPa}; \quad \nu = 0.186 \qquad (1)$$

It is, however, widely recognised that, even when accurate control of the injection parameters is pursued, the mechanical properties of cemented soil present significant random variations within a single column. A collection of data from different field trials reported in Table 2 shows that relatively high values are typically obtained of soilcrete strength from laboratory tests, although coefficient of variation as large as 0.5 must be expected depending on the original soil type [10]. The coefficient of variation estimated by means of statistical analysis of the tests of the present case is equal to 0.19.

Table 1.
Injection parameters adopted for the trial columns at Bojszowy Nowe [6]

Cement type	Grout density (kg/m^3)	Injection pressure (MPa)	Number of nozzles	Nozzle diameter (mm)	Monitor lifting speed (m/s)	Reinforcement for columns P1, P2 and P4
CEM II BS 32.5R	1500	35	2	2.5	0.0166	HEB 240

Table 2.
Variation of uniaxial compressive strength of cemented soil from different field trials [20]

Case study	Soil type	Number of tests	Average value of uniaxial compressive strength (MPa)	CV(σ_c)	Reference
Vesuvius	silty sand	26	8.14	0.40	Croce and Flora (1999)
Polcevera	sandy gravel	26	10.49	0.36	Croce et al. (1994)
Fadalto	clean gravel	71	12.34 – 13.78	0.42	Croce et al. (1994)
Japan	clay	50	10.77 – 11.04	0.49	Ichihashi et al. (1992)
Bojszowy	sand	30	21.12	0.19	Bzówka (2009)

Table 3.
Variation of columns diameter obtained from different field trials [20]

Case study	Number of columns	Average diameter min. – mix. (m)	Number of data	CV(D)	Soil type	References
Vesuvius	6	0.71 – 1.11	71	0.06	silty sand	Croce and Flora (1999)
Polcevera	4	1.06 – 1.20	50	0.19	sandy gravel	Croce et al. (1994)
Barcelona	37	0.35 – 0.64	97	0.18	clay	Arroyo et al. (2007)
Amsterdam	4	0.72 – 1.37	72	0.16	clay-sand	Langhorst et al. (2007)

The cross sectional dimensions of columns were measured in the top 2 m by discovering the upper part of P1 and P3 columns. Unluckily it was not possible to extend this measurement to the lower part due to the presence of buildings close to the test area. However, the measured range of diameters, depicted with the shaded area of Fig. 3, is in a good accordance with the values given by a theoretical model proposed for single fluid jet grouting [19]. This model relating the average diameter of columns to the initial soil properties (unit weight and strength parameters) and to the adopted injection system (quantified by the number and diameter of nozzles, injection velocity, monitor lifting speed) shows a typical shape of columns injected in sandy soils. As an effect of the soil strength increase with depth, a systematic reduction of diameters is in fact seen giving a funnel shape to the columns.

Together with this systematic effect, a random variation of cross section is frequently seen on jet grouting columns as a consequence of erratic local changes of soil properties. A statistical analysis performed on data collected from different case histories [10] shows that column diameters typically follow normal distributions with larger standard deviations for coarser soils compared with finer ones (Table 3).

The trial loading program for the four columns P1÷P4 was conceived to alternate axial compression with pull out. Tests were in fact carried out as reported in Table 4 with two subsequent phases, the latter carried out ten months after the end of the former one. The loads were applied on the top of columns by a system (Fig. 4) of transverse beams and anchoring jet grouting columns designed to provide maximum capacities of 4000 and 1500 kN respectively for downward loading and uplift tests.

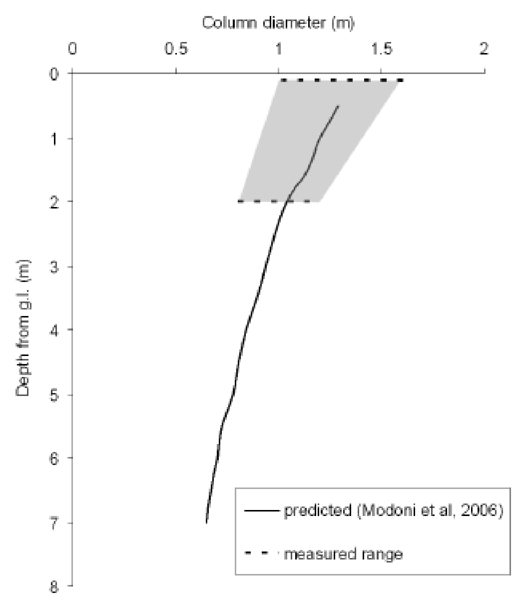

Figure 3.
Column diameter profile

Table 4.
Sequences of loading phases carried on the trial columns ([5], [6])

Column	P1	P2	P3	P4
I phase	Compression	Pull-out	Compression	Pull-out
II phase	Pull-out	Compression	Compression	Compression

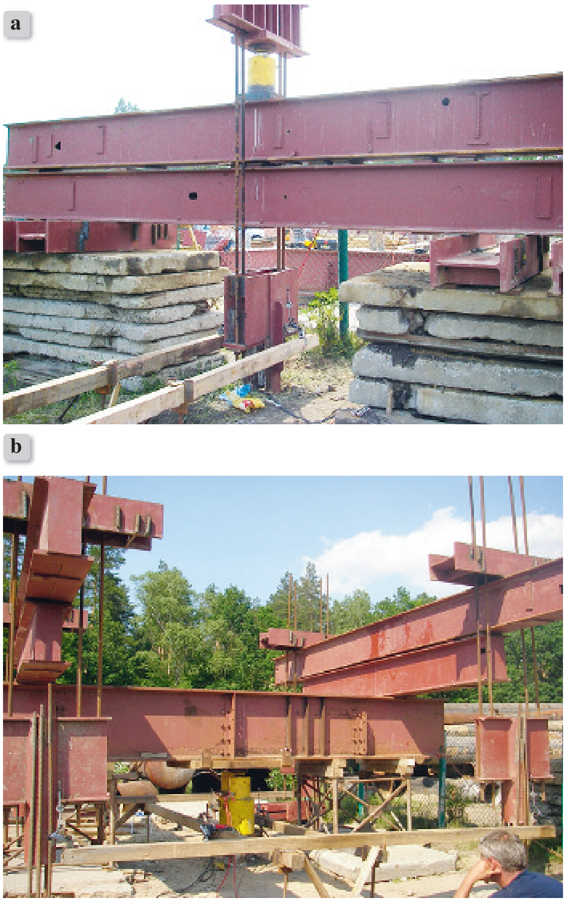

Figure 4.
Stands for compressive load (a) and pull-out (b) tests ([5], [6])

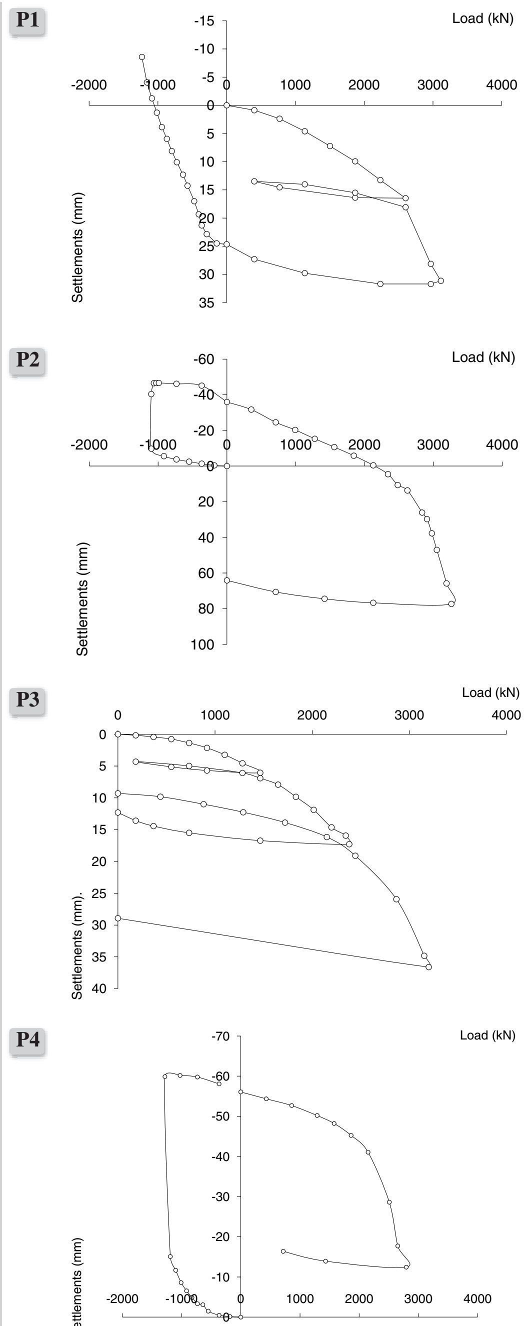

Figure 5.
Experimental results of axial load tests and numerical simulations (downward movements and loads are assumed as positive)

The total load settlement experimental curves of the four columns, reported in Fig. 5 by adjoining the results of the two subsequent phases, raise the following observations:

- independently on their previous loading histories, columns are able to sustain upward loads larger than 1200 kN, downward loads larger than 3200 kN; this latter value is 20-30% larger than the limit axial loads calculated for replacement piles with literature methods [25];
- the similarity between the two curves obtained on P1 and P3 columns during primary loading shows

that the inclusion of the steel reinforcement (in P1 column) is not particularly effective in reducing the foundation settlements. Negligible deformations can be in fact obtained within unreinforced columns P3 by looking at the settlements recorded at different depths (Fig. 6);

- pull-out tests performed on P2 and P4 columns show a similar stiff initial response, followed by a sudden uplift caused by slippage of the steel reinforcement within the columns;
- in the second phase of tests on columns P1 and P2, when the load is reversed, a particularly soft response is obtained as an effect of the damage caused to the surrounding soil by the initial loading in the opposite direction.

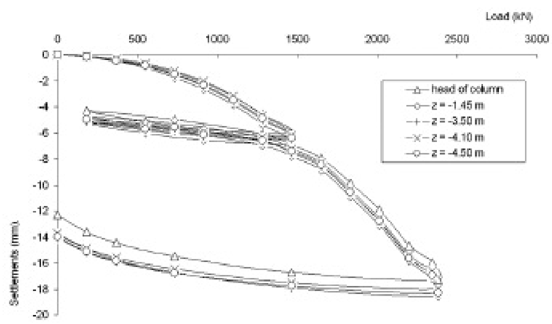

Figure 6.
Settlement at different depth of column P3 versus load applied on column's top

3. NUMERICAL SIMULATIONS

The numerical simulations have been conducted with a FEM code [3] by assuming an axially symmetric column's profile (Fig. 3) and by calculating the soil properties with in situ tests results. The subsoil has been subdivided in different layers, each of them 0.5 m thick, whose mechanical response has been simulated with a linear elastic perfectly plastic model (Mohr-Coulomb). According to the laboratory tests natural unit weights equal to 18.4 kN/m^3 and 19.2 kN/m^3 have been assigned to the soil layers respectively above and below water table. The friction angle Φ' (Fig. 7a) has been calculated by considering the dependency on relative density expressed for a medium uniform sand by the Hilf [15]:

$$\phi'(°) = 27 + 13 \cdot D_r \qquad (2)$$

The relative density Dr has been calculated as a function of q_c with the following relation proposed by Baldi et al. [1].

$$D_r = \frac{1}{C_2}\ln\left(\frac{q_c}{C_1 \cdot (\sigma')C_0}\right) \qquad (3)$$

with $C_0 = 0.55$, $C_1 = 181$, $C_2 = 2.61$ and q_c expressing the measured tip resistance (in kPa) of CPT test.

The dilatancy angle ψ (Fig. 7a) has been calculated as:

$$\sin\psi = \frac{\sin\varphi' - \sin\varphi'_{cv}}{1 - \sin\varphi' \cdot \sin\varphi'_{cv}} \qquad (4)$$

where $\varphi'_{cv} = \varphi' - 3 \cdot \lfloor D_r \cdot (10 - \ln p'_f) - 1 \rfloor$ [2]

and $p'_f = \sigma'_v \cdot \left(1 - \tfrac{2}{3}\sin\varphi'\right)$.

The Young's modulus (Fig. 7b) has been calculated with the procedure suggested by Marchetti [18], i.e. by calculating a constrained modulus M_{DMT} with the following relation based on the measured DMT indexes, and by assuming a Poisson ratio equal to 0.3 as typical for sandy soils:

$$M_{DMT} = R_M \cdot E_D \qquad (5)$$

where $R_M = R_{M0} + (2.5 - R_{M0}) \cdot \log K_D$

and $R_{M0} = 0.14 + 0.15 \cdot (I_D - 0.6)$

Jet grouting columns production is simulated by simply substituting the original soil with cemented material, i.e. without introducing any modification at the interface. A Mohr-Coulomb model with the properties reported in eq.1 has been adopted to reproduce behaviour of cemented material. In Fig. 8 the entire experimental load settlement curve of test P3 is compared with its numerical simulation, this latter calculated by assigning the sequence of displacements measured at the columns top during the test. The comparison between the two curves shows a quite satisfactory capability of the model to reproduce the load settlement response of column. Possibility of improving simulations by adopting more advanced soil models able to better capture complexity of soil responses (non linearity, dependency of strength and dilatancy on the mean effective stress) has been discarded in the present case due to the lack of laboratory tests and to the arbitrary calibration of parameters based on in situ tests.

A classical question on foundation reinforcements regards the mechanical interaction with the surrounding soil, which is known to be deeply affected

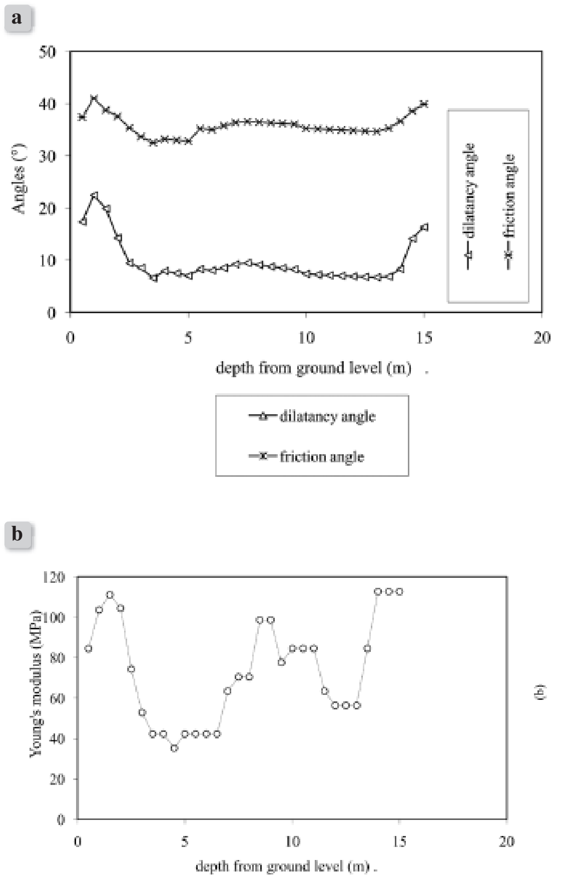

Figure 7.
Profiles of friction and dilatancy angles (a) and Young's modulus (b)

by the executive technology. For foundation piles the relative weight between the loads transferred at the base (P) and along the lateral surface (S) and their development with settlements has been widely studied topic. Several experimental campaigns have focused on the distribution of axial loads along the pile axis indirectly obtained from measurement of vertical deformations at different depths. Similar experiments are not usual on jet grouting basically due to the difficulties in quantifying with enough confidence, cross sectional dimensions and mechanical properties of columns.

The evolution with settlements of the loads at the base and the side surface for axially loaded jet grouting column is here calculated with the previously described numerical model (Fig. 9). A clearly evident result of this analysis is that both load fractions require relatively increasingly larger displacements to be mobilised with the consequence that serviceability represents the most restrictive condition for the design of

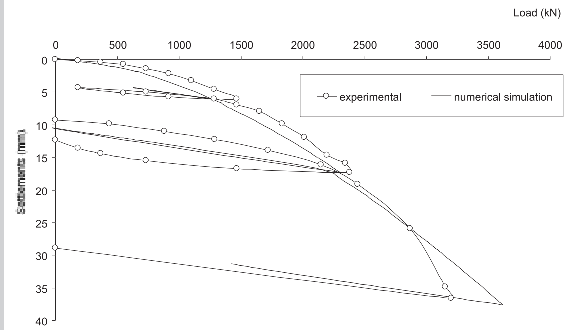

Figure 8.
Comparison between experimental and calculated load settlement curves (test P3)

jet grouted foundation. Following a procedure typically adopted for large diameter piles, the limit loads (P_{lim} and S_{lim}) are thus defined as those corresponding to a prescribed settlements (w = 0.05 D).

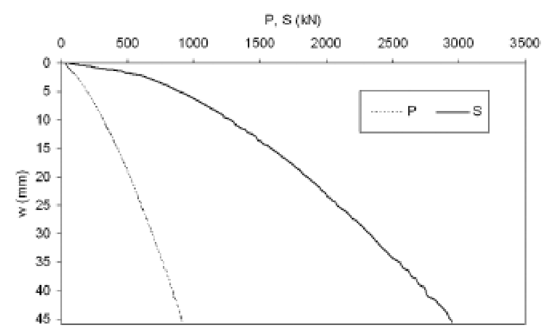

Figure 9.
Mobilisation of loads at the base and lateral surface of jet grouting column

When considering the column's profile in Fig. 3 (giving a base diameter D_b= 0.65 m and a variable diameter along column depth), the two limit loads P_{lim} and S_{lim} reported in Table 5 can be obtained from Fig. 9.

It is worth noting that these values are similar to the ones calculated with the following equations:

$$P_{\lim} = p_{\lim} \cdot \pi \cdot \frac{D_b^{\ 2}}{4} \tag{6a}$$

$$S_{\lim} = \int_L \pi \cdot \overline{D} \cdot s_{\lim} \cdot dz \tag{6b}$$

where the unit values p_{lim} and s_{lim} are given in Fig. 10 as functions of unit CPT tip resistance from liter-

Table 5.
Sequences of loading phases carried on the trial columns

	P_{lim} (kN)	S_{lim} (kN)
FEM calculation	732	2954
eq.6	862	2930

ature (respectively p_{lim} from Wright & Reese, 1977, s_{lim} from Bustamante, 2002). In particular, p_{lim} represents the unit limit base load of bored piles [25], while s_{lim} is the unit side resistance of jet grouting columns injected in sandy soils [4].

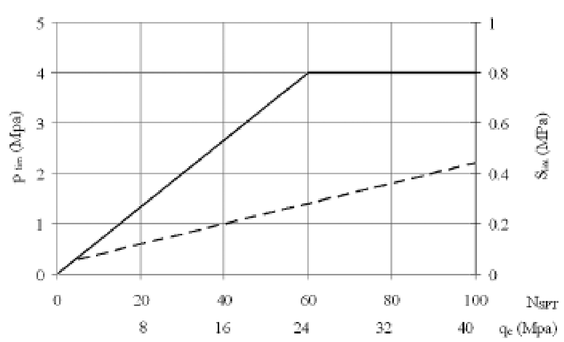

Figure 10.
Limit unit load at the base and lateral surface of columns

The mobilisation of the two load fractions is studied by plotting normalised curves in Figs. 11.a and b. Settlements in each plot are scaled by the column diameter (D_b= 0.65 m for the base, the average values $\overline{D}$ = 0.92 m for the side surface) and loads are scaled by previously calculated limit values (P_{lim} and S_{lim}). In both figures two shaded areas are also reported representing the ranges of mobilisation curves experimentally observed on large diameter piles bored in cohesionless soils [22]. The comparison of the curves obtained with the FEM calculation for jet grouting column with these latter clearly shows that, while for the column base the load transfer mechanisms are similar to those typically activated on bored piles, significant differences appear in the transfer mechanisms on the lateral surface. In particular, for this latter a more ductile response is seen on jet grouting columns compared with piles. A possible explanation consists in the irregular shape of jet grouting column, which promotes transfer of load based on compressive more than on tangential stresses in the surrounding soil.

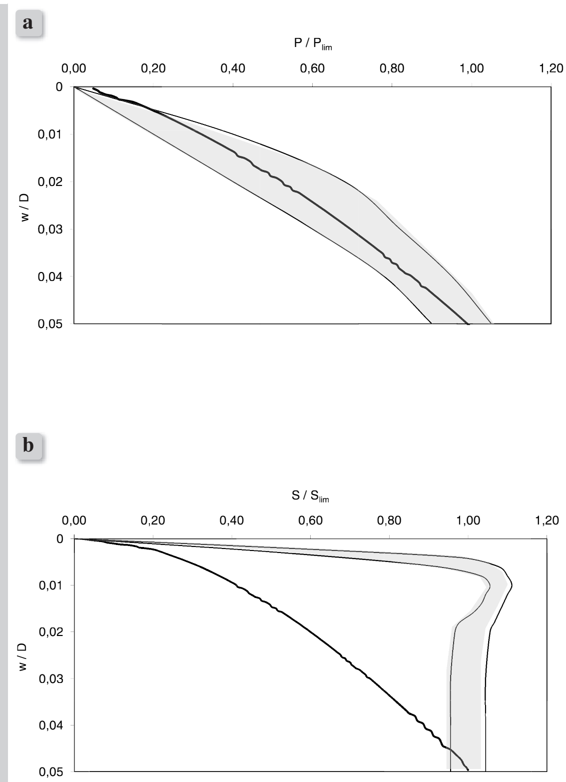

Figure 11.
Mobilisation of the column base (a) and side (b) resistance calculated with the FEM model (the shaded areas represent mobilisation for bored piles [22]

To better explore this issue a further analysis is developed in Fig. 12 where the load fraction transferred by the side shaft is plotted versus the settlement ratio w/D. Three different columns have been considered in this analysis each of them with a different shape but with the same average diameter calculated for the field trial ($\overline{D}$ = 0.92 m). The first case represents a column shape in Fig. 3, where a diameter reduction is deterministically assigned with depth (funnel). The second case represents a perfectly cylindrical column (constant diameter), while the third is representative of a column with randomly variable diameters.

Diameters in this latter case have been calculated with Monte Carlo method by assigning a normal distribution and a coefficient of variation equal to 0.2.

The plot shows that for all cases a larger part of loads is applied to the surrounding soil by the column side. Furthermore, variation of diameters, either if caused by a systematic reduction with depth or by a random variation, is responsible for an increase of load transferred from the column side. S is in fact equal to about 80% of the total amount for columns with variable diameters, equal to 65% for cylindrical column. It is worth noting that this latter value becomes even lower if a reducing factor is introduced at the interface strength, as is necessary to simulate soil disturbance induced by bored piles installation.

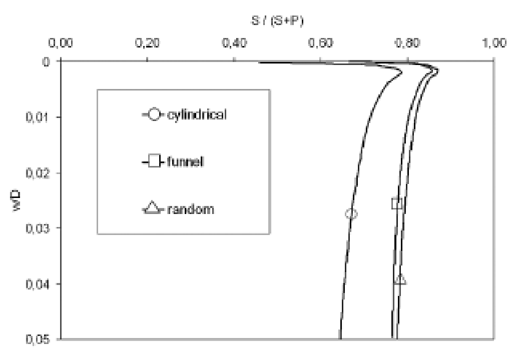

Figure 12.
Load settlement simulations for different column shape

A comment is finally devoted to the variation of mechanical properties of cemented soil, which has not been considered in the above presented analysis. A comparison not reported in the paper shows that random variations of strength and stiffness of cemented soil (as shown in Table 2) produce negligible effects on the load settlement response. This result can be attributed to the relatively higher stiffness of the cemented material compared with the surrounding soil. It is, however, recalled that a reduction of cemented soil strength, associated with random variations of column diameter, may determine weaker sections where structural collapse becomes possible [10].

4. CONCLUSIONS

Despite large use of jet grouting for foundation engineering, design predictions are still based on simple assumptions, often derived from piled foundations practice. Experimental investigations able to characterise the response of columns, with particular reference to the interaction with the surrounding soil, are cumbersome mainly due to the difficulties in establishing dimensions and mechanical properties of columns. Quantitative observations are thus limited and not clearly interpreted. In the present case a field trial campaign consisting of alternated axial load and pull out tests has been presented together with its interpretation by means of a numerical analysis. Experimental results show that deformation of columns plays a limited role to the relatively higher stiffness of soilcrete compared with the deformability of surrounding soil. Failure during pull-out tests is caused by the slippage of internal steel reinforcement. Independently on their previous loading histories, jet grouting columns are able to sustain axial loads 20-30% larger than expected for bored piles of similar average dimensions.

According to the numerical back-analysis the difference arises from irregular shape of columns, which enhances more effective transfer of loads from the column shaft compared with perfectly cylindrical ones. It has, however, been observed that mobilisation of lateral stresses follows a trend similar to the lower base, i.e. its activation require relatively large displacements. This result implies that serviceability is the most restrictive limit condition to be considered in the foundation design. Following a procedure already adopted for large diameter piles, a simple limit serviceability analysis has been suggested based on a maximum tolerable settlement (w/D = 0.05). Corresponding limit loads have been calculated from the numerical back analysis and in a good agreement with those provided by the literature.

REFERENCES

[1] *Baldi G., Bellotti R., Ghionna V., Jamiolkowski M., Pasqualini E.*; Interpretation of CPT and CPTUs, 2nd part: Drained penetration of sand, Proc. 4th Int. Geotech. Seminar Singapore, 1986, p.143-156

[2] *Bolton M.D.*; The strenght and dilatancy of sands, Geotechnique 36, No.1, 1986, p.65-78.

[3] *Brinkgreve R.B.J., Vermeer P.A.*; Plaxis Manual, version 7.2., A.A. Balkema Rotterdam, Delft, the Nederlands, 2000

[4] *Bustamante M.*; Jet grouting columns. Report of the Seminar: Pathology of soils and foundations, Hammamet (Tunisia), 2002

[5] *Bzówka J., Pieczyrak J.*; Pull out and load tests for jet grouting columns. Proc. of the XI Baltic Sea Geotechnical Conference, Polish Committee on Geotechnics & Gdansk University of Technology, Gdansk 2008

[6] *Bzówka J.*; Interaction of jet grouting columns with subsoil, Monograph, Silesian University of Technology Publishers, Gliwice 2009 (in Polish)

[7] *Cicognani M., Garassino A.L.*; Controls of the execution of jet grouting treatments. Proc. of the XVII National Conference of Geotechnical Engineering, Taormina (Italy), 1989, p.97-105 (in Italian)

[8] *Croce P., Chisari A., Merletti T.*; Investigations on jet grouting treatments for the foundations of highway viaducts, Rassegna dei Lavori Pubblici, 1990, p.249-260 (in Italian)

[9] *Croce P., Gajo A., Mongiovì L., Zaninetti A.*; An experimental assessment of the effects jet grouting, Rivista Italiana di Geotecnica, 2, 1994, p.91-101 (in Italian)

[10] *Croce P., Modoni G.*; Numerical Modelling of Jet-Grouted Foundations, V European Conference on Numerical Methods in Geotechnical Engineering, Paris, September 2002

[11] *Croce P., Flora A.*; Analysis of single fluid jet-grouting, Geotechnique, 50, No. 6, 2000, p.739-748

[12] *Falcão J., Pinto A., Pinto F.*; Case Histories and work performance of vertical jet grouting solutions, Proc. of the IV Int. Conf. on Ground Improvement, Helsinki 2001, p.165-171

[13] *Garassino A.L.*; Use of jet grouting columns for provisional reinforcement, Proc. of the XV National Conference of Geotechnical Engineering, Spoleto, II, 1983, p.155-161 (in Italian)

[14] *Garassino A.L.*; Design procedures for jet-grouting. Proc. of a seminar organised by THL Foundation equipment Pte Ltd, and Gaggiotti Far East Singapore, 1997, website

[15] *Hilf J.W.*; Compacted fill. In Foundation Engineering Handbook (second edition), edited by H. Yang Fang, Van Nostrand Reinhold, New York 1991, p.249-316

[16] *Kutzner C.*; Grouting of Rock and Soil, Balkema editions, Rotterdam 1996

[17] *Maertens J., Maekelberg W.*; Special applications of the jet-grouting technique for underpinning works, Proc. of the XV ICSMFE, Istanbul (Turkey), 2001, p.1795-1798

[18] *Marchetti S.*; In Situ Tests by Flat Dilatometer, ASCE Jnl GED, Vol. 106, No. GT3, Mar. 1980, p.299-321

[19] *Modoni G., Croce P., Mongiovì L.*; Theoretical modelling of jet grouting, Géotechnique, 56 (5), 2006, p.335-347

[20] *Modoni G., Bzówka J., Pieczyrak J.*; Axial loading of jet grouting columns, Proc. of the 14th Danube-European Conference on Geotechnical Engineering „From research to design in European Practice", Session 6: Numerical and physical models in geotechnical design, Bratislava, Slovak Republic, 2-4 June 2010

[21] *Perelli Cippo A., Tornaghi R.*; Soil improvement by jet grouting, Underpinning, Surrey University Press, S. Thorburn and J.F. Hutchison eds., 1985, p.276-292

[22] *Reese L.C., O'Neill M.W.*; Drilled shafts: construction procedure and design methods, U.S. Depth., of Transp F.H.A. Publ. H.I., 1988, p.88-42

[23] *Saglamer A., Duzceer R., Gokalp A., Yilmaz E.*; Recent applications of jet grouting for soil improvement in Turkey, Proc. of the XV ICSMGE, Istanbul, 2001, p.1839-1842

[24] *Shibazaki M., Ohta S.*; A unique underpinning of soil solidification utilizing super-high pressure liquid jet, Proc. of the Conference of Grouting in Geotechnical Engineering, New Orleans 1982, p.680-693

[25] *Wright S.J., Reese L.C.*; Construction of drilled shaft and design for axial loading, U.S. Depth of Transp. Drilled shaft manual, Vol. I, 1977, p.140